Small-Scale Cyclic Tests on Nonslender Piles Situated in Sand

test results

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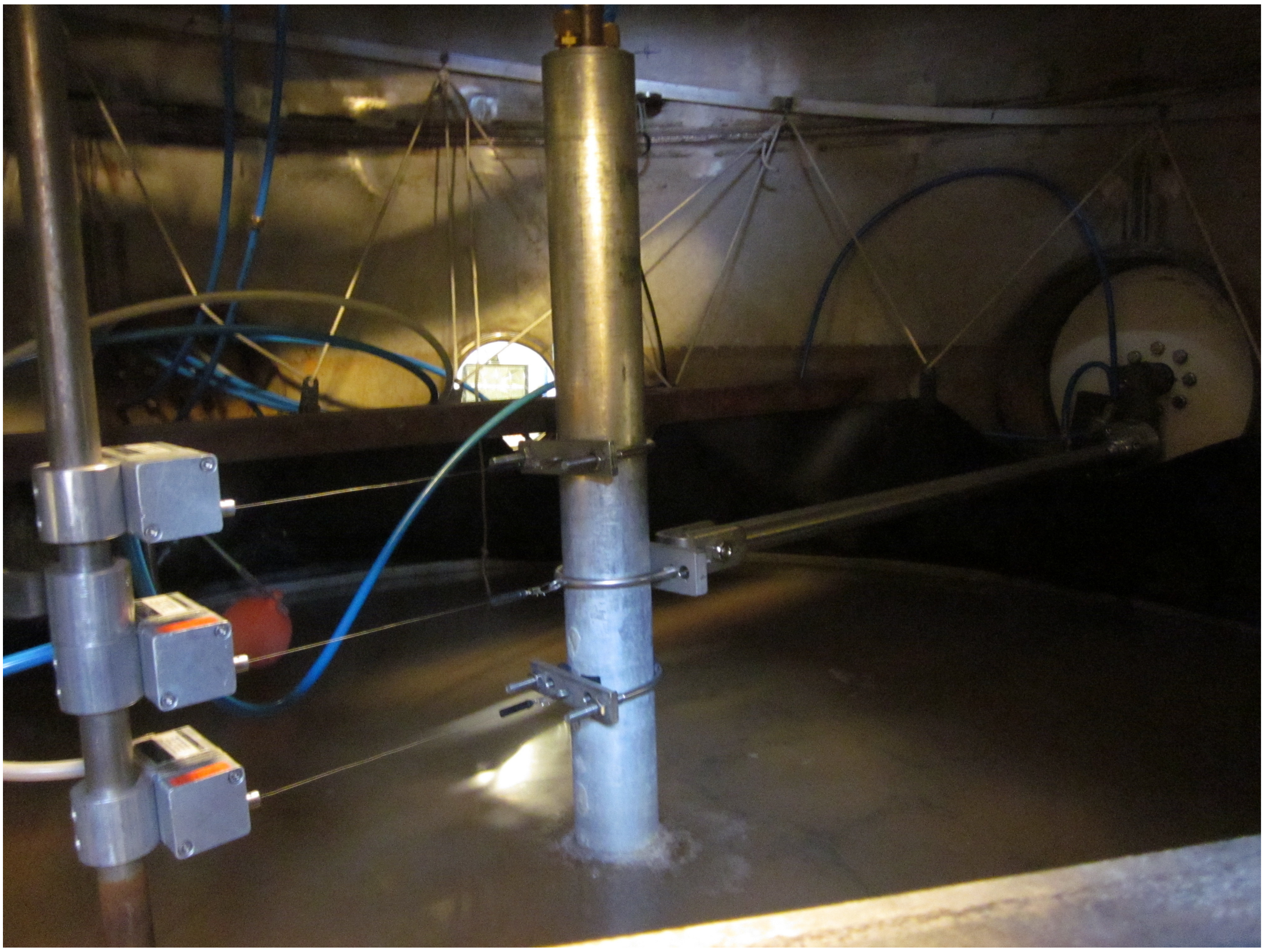

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by

Søren Peder Hyldal Sørensen
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October 2011

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Contents

Introduction

In the period from August 2011 till October 2011 a series of small-scale tests on pile foundations has been conducted at Aalborg University. In all the tests, the piles have been exposed to cyclic loading consisting of 20-25 load cycles and all the tests have been conducted in a pressure tank. The objective of the tests has been to investigate the effect of pile diameter, length to diameter ratio and cyclic loading on the soil response for non-slender piles in sand.

Piles with outer diameters, D, varying between 80 and 100 mm, pile embedment lengths, L_p, between 240 and 500 mm and length to diameter ratios (slenderness ratios), L_p/D, from 3 to 6 have been tested. Hereby, the scales of the tested piles are approximately between 1:40 and 1:80 of a full-scale monopile foundation for an offshore wind turbine.

One of the significant uncertainties when conducting small-scale tests is that the stresses in the soil are small when comparing to a full-scale pile. As the soil parameters depend on the stress level this leads to uncertainties when trying to scale the small-scale tests to a full-scale monopile foundation. Further, the determination of the soil parameters is uncertain for low stress levels. When conducting the tests in a pressure tank it is possible to add an excess pressure (overburden pressure), P_0. In order to increase the effective stresses in the soil, and not the pore pressure, a membrane have been placed on top of the soil for the tests conducted with overburden pressure. The overburden pressure has been varied between 0 and 100 kPa. An overburden pressure of 100 kPa corresponds to the effective vertical stress in the soil at a depth of approximately 10 m.

The test setup and the preparation prior to testing are similar to the quasi-static tests on laterally loaded piles described in Sørensen and Ibsen (2011). The test setup and preparation prior to testing is therefore not described in this report. In order to apply two-way loading to the test piles an aluminium bar has been positioned between the hydraulic piston and the pile. In the tests described by Sørensen and Ibsen (2011) a steel wire was used.

The test programme is shown in Table 1.

TABLE 1. TEST PROGRAMME. SG DENOTES STRAIN GAUGES.

Test	Pile diameter, *D* [mm]	Embedded pile length, *L* [mm]	Pile slenderness ratio, *L*/*D* [-]	Overburden pressure, P_0 [kPa]	Number of strain gauges measuring
1	80	240	3	0	0
2	80	240	3	50	0
3	80	240	3	100	0
4	80	320	4	0	11
5	80	320	4	50	11
6	80	320	4	100	11
7	80	400	5	0	11
8	80	400	5	25	11
9	80	400	5	50	11
10	80	400	5	75	11
11	80	400	5	100	11
12	80	480	6	0	11
13	80	480	6	50	11
14	80	480	6	100	11
15	100	500	5	0	0

References

Sørensen, S. P. H. & Ibsen, L. B. 2011. Small-scale quasi-static tests on non-slender piles situated in sand – Test results. *DCE Technical Report No. 112, Department of Civil Engineering, Aalborg University, Denmark.*

Soil parameters and test results

In the following the test results for the 29 conducted tests are presented. The results and interpretation of the conducted CPT's prior to each test is presented. Further, the direct measurements from the tests are presented. For the tests with strain gauges attached the distribution of pile displacement, pile rotation, pile curvature, pile bending moment and soil resistance with depth and furthermore *p-y* curves determined based on the direct measurements are shown.

Test 1: D = 80 mm, L_p = 240 mm and P_0 = 0 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 10/11-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 0
Embedded pile length (mm): 240	**Overburden pressure (kPa):** 0
Slenderness ratio, *L/D*: 3	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments:	

Soil parameters:

TABLE 2. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.75-0.91	52.0-54.5	17.4-20.5	10.1-10.4	-	0.23

Test results:

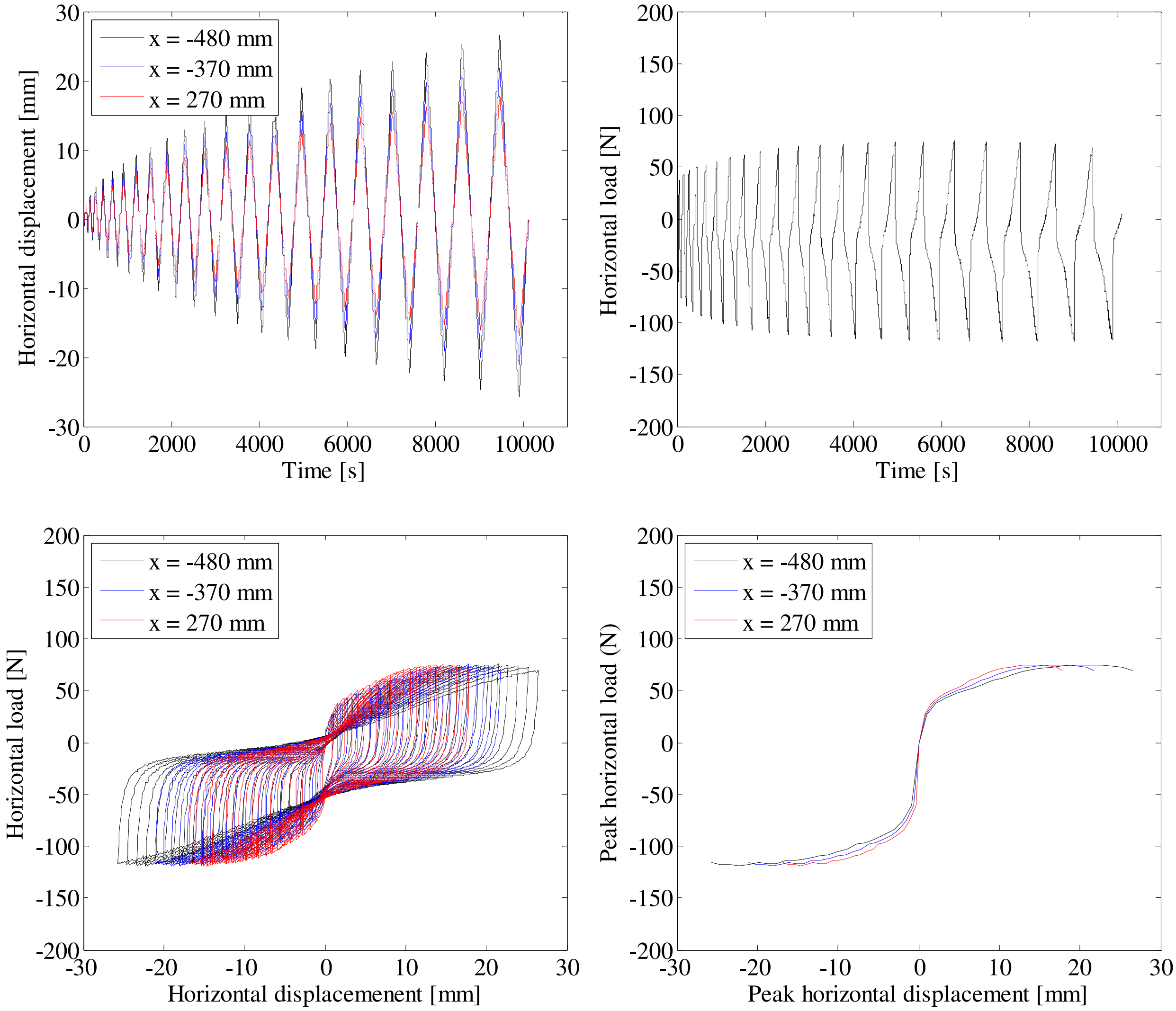

FIGURE 1. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT.

Test 2: D = 80 mm, L_p = 240 mm and P_0 = 50 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 7/10-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 0
Embedded pile length (mm): 240	**Overburden pressure (kPa):** 50
Slenderness ratio, *L/D*: 3	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of 8 l/h.	

Soil parameters:

TABLE 3. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.75-0.91	48.0-51.0	16.3-19.5	10.1-10.4	23.6-31.8	0.23

Test results:

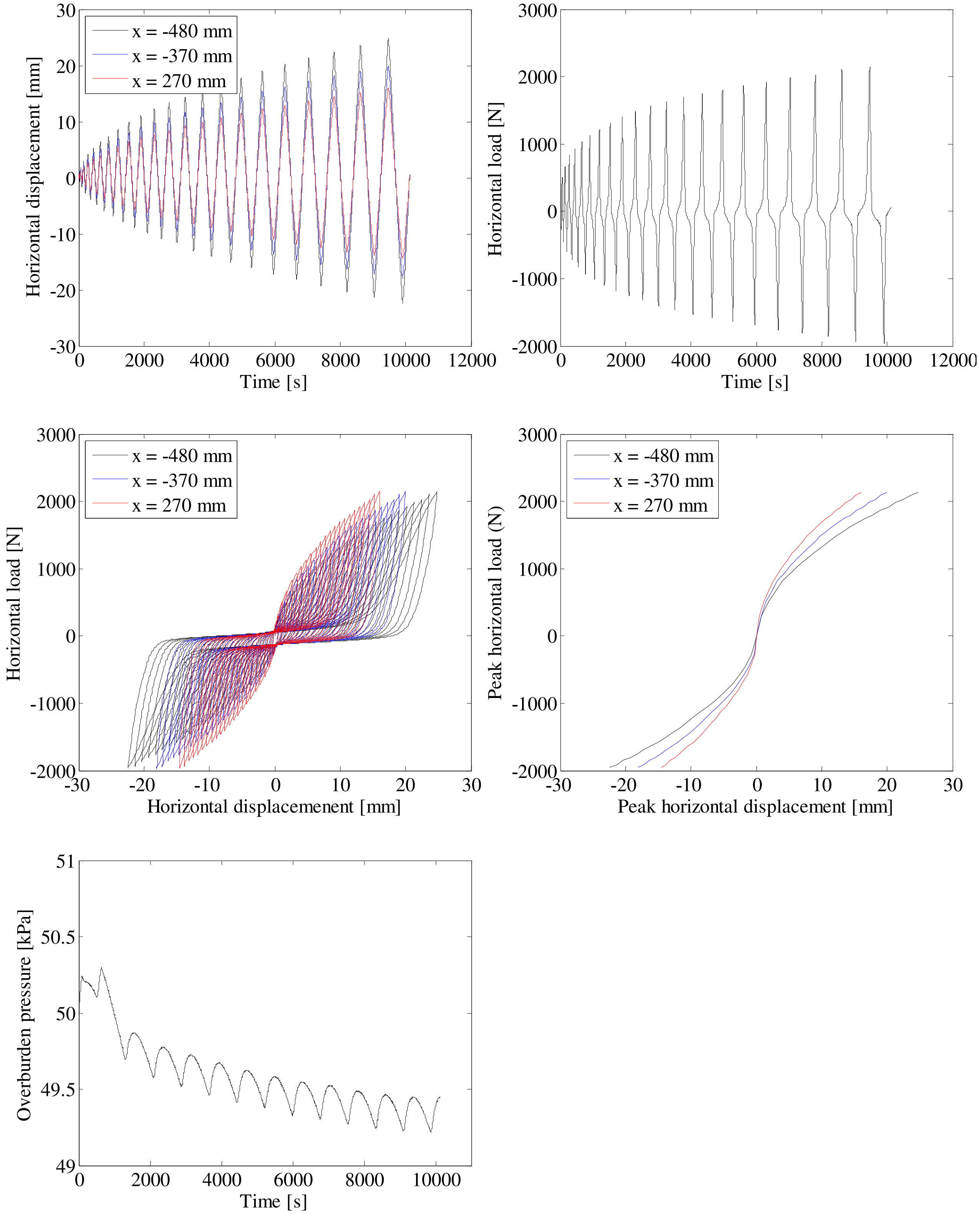

FIGURE 2. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 3: D = 80 mm, L_p = 240 mm and P_0 = 100 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 9/10-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 0
Embedded pile length (mm): 240	**Overburden pressure (kPa):** 100
Slenderness ratio, *L/D*: 3	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments:	

Soil parameters:

TABLE 4. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.75-0.91	45.3-48.1	15.4-18.6	10.1-10.4	37.8-51.5	0.23

Test results:

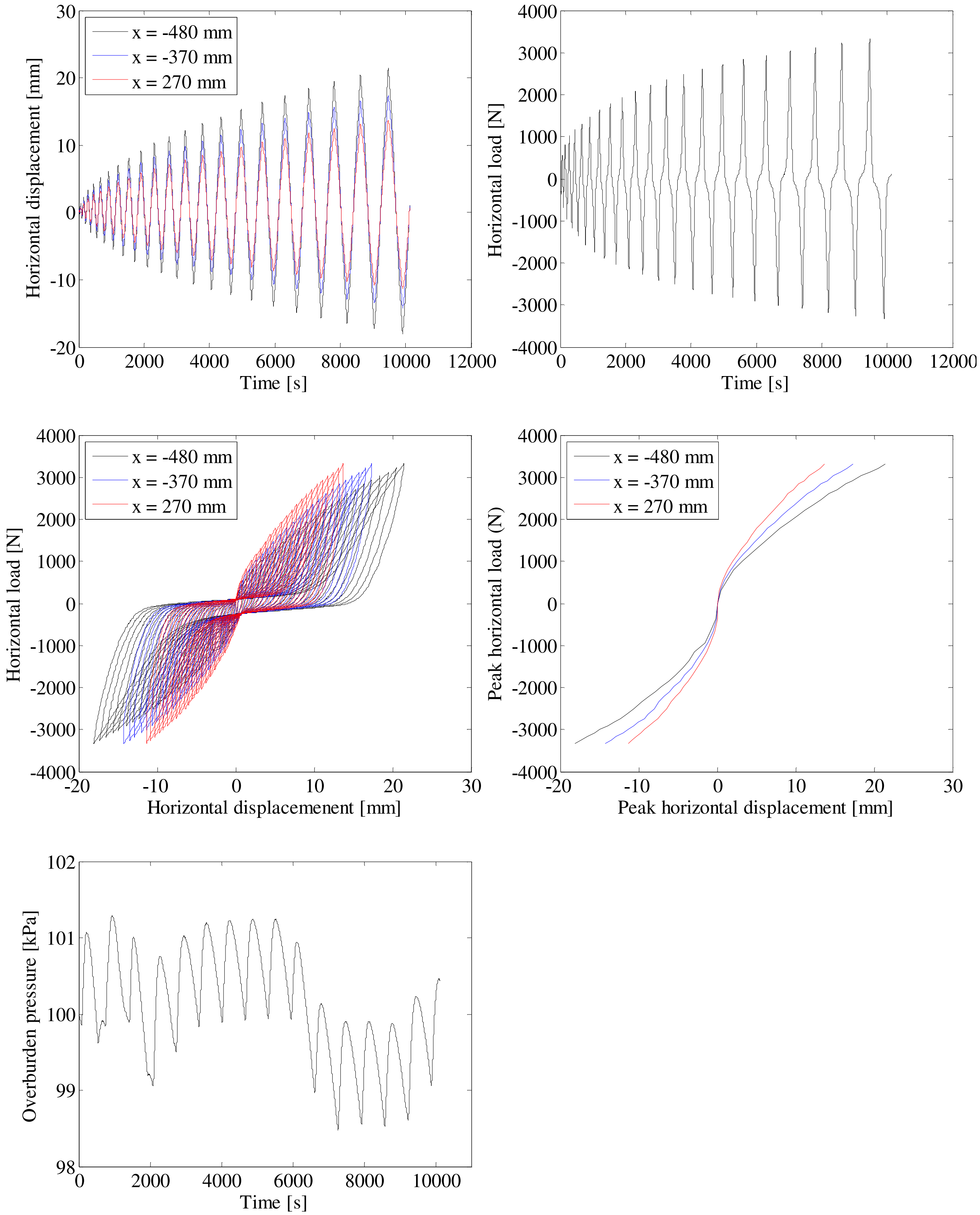

FIGURE 3. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 4: D = 80 mm, L_p = 320 mm and P_0 = 0 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 23/9-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 320	**Overburden pressure (kPa):** 0
Slenderness ratio, *L/D*: 4	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas & S. P. H. Sørensen
Comments:	

Soil parameters:

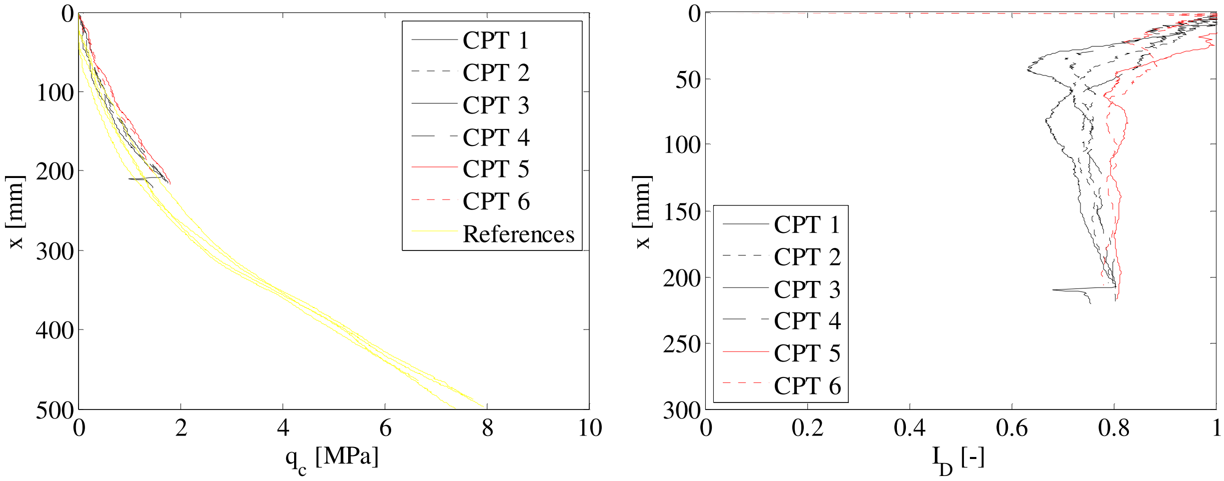

FIGURE 4. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 5. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.78	52.7	18.0	10.2	-	0.23

Test results:

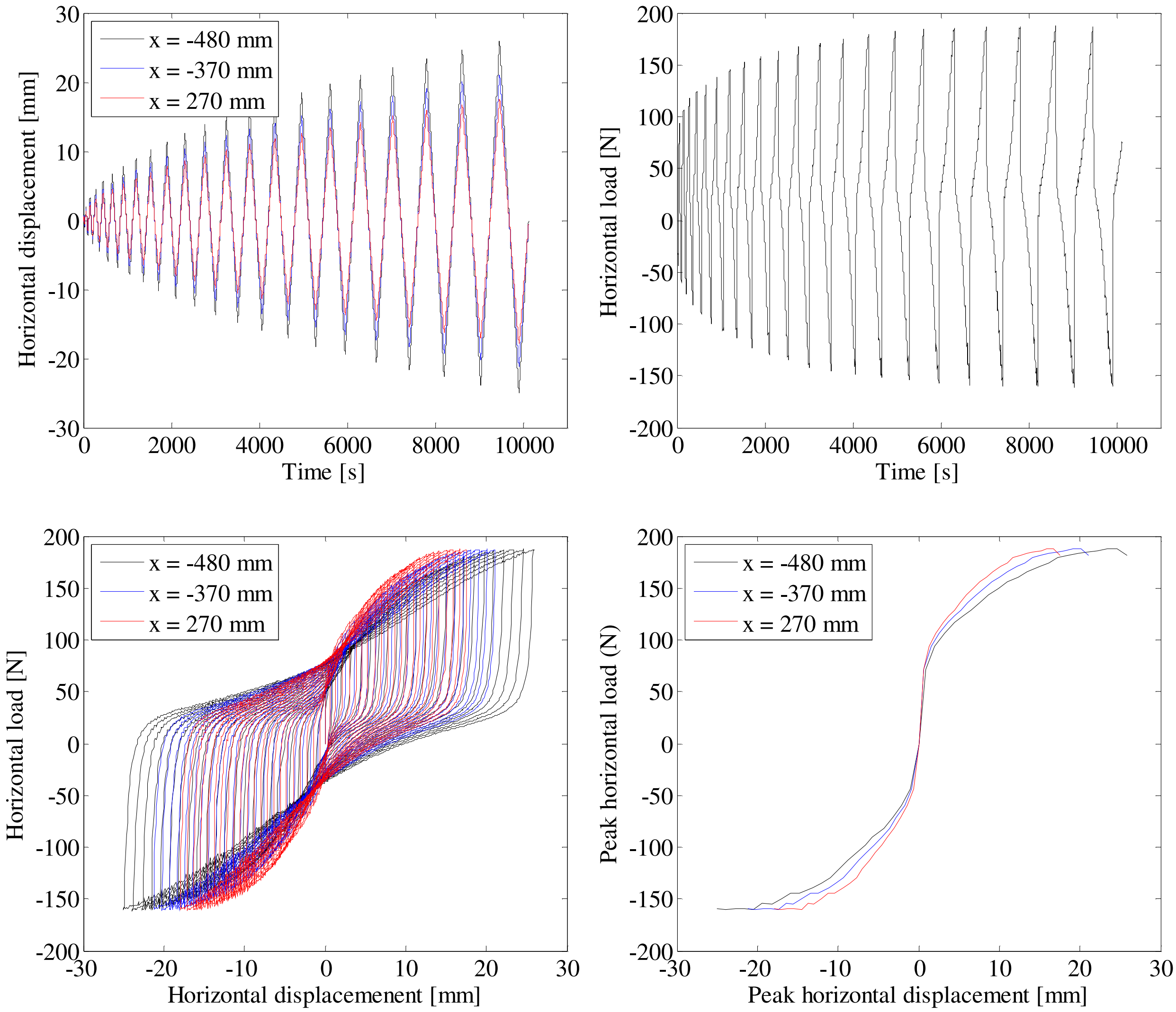

FIGURE 5. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT.

Test 5: D = 80 mm, L_p = 320 mm and P_0 = 50 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 25/9-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 320	**Overburden pressure (kPa):** 50
Slenderness ratio, *L*/*D*: 4	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments:	

Soil parameters:

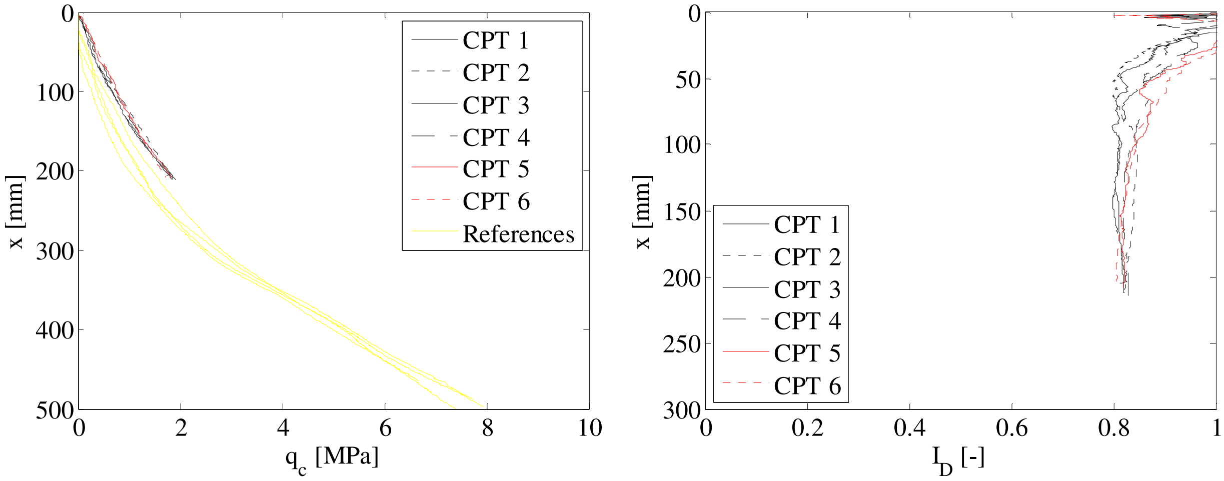

FIGURE 6. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 6. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.82	49.4	17.7	10.3	27.3	0.23

Test results:

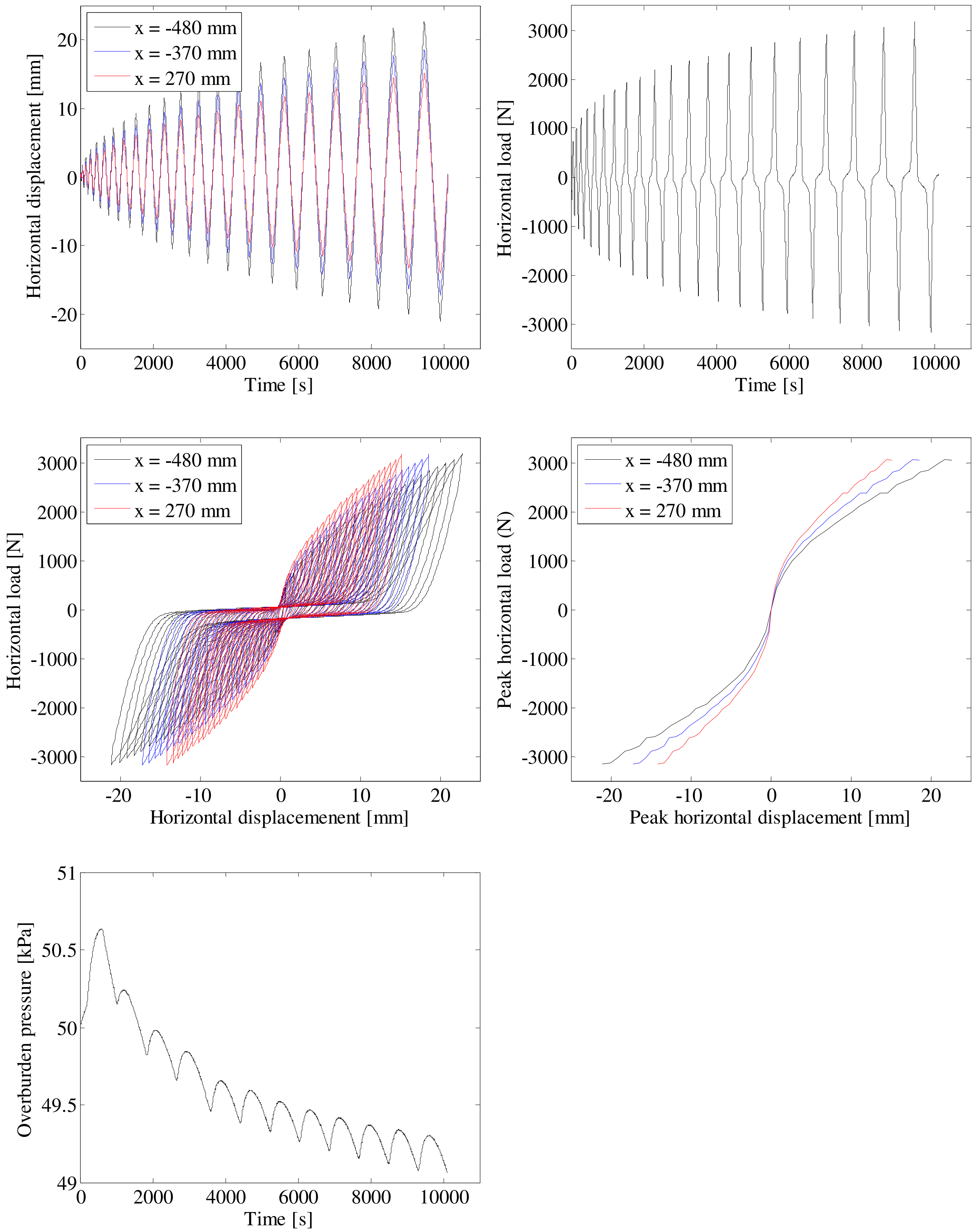

FIGURE 7. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 6: D = 80 mm, L_p = 320 mm and P_0 = 100 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 2/10-2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 320	**Overburden pressure (kPa):** 100
Slenderness ratio, *L/D*: 4	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of 8 l/h.	

Soil parameters:

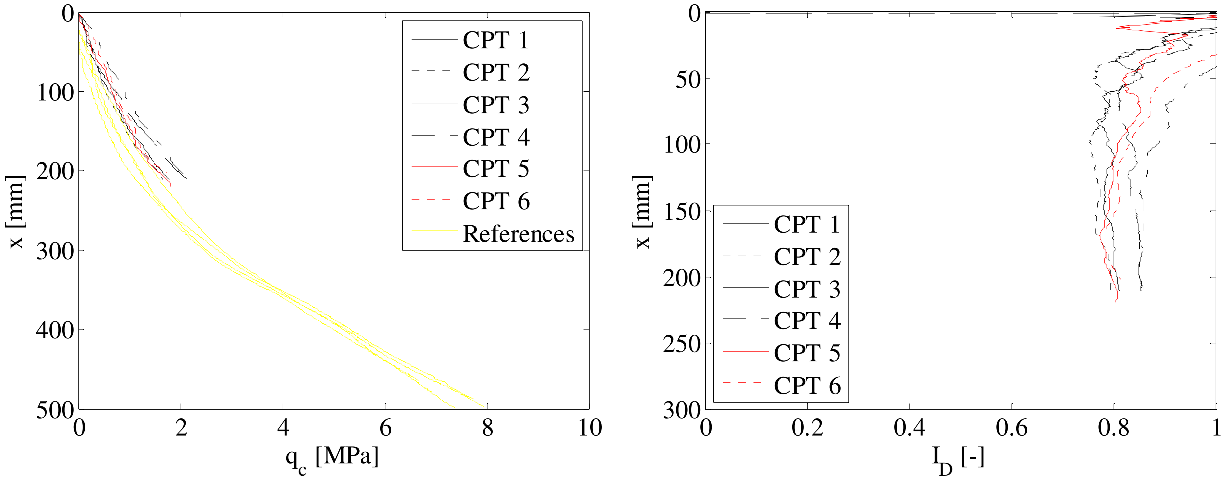

FIGURE 8. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 7. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.82	46.5	16.7	10.3	42.5	0.23

Test results:

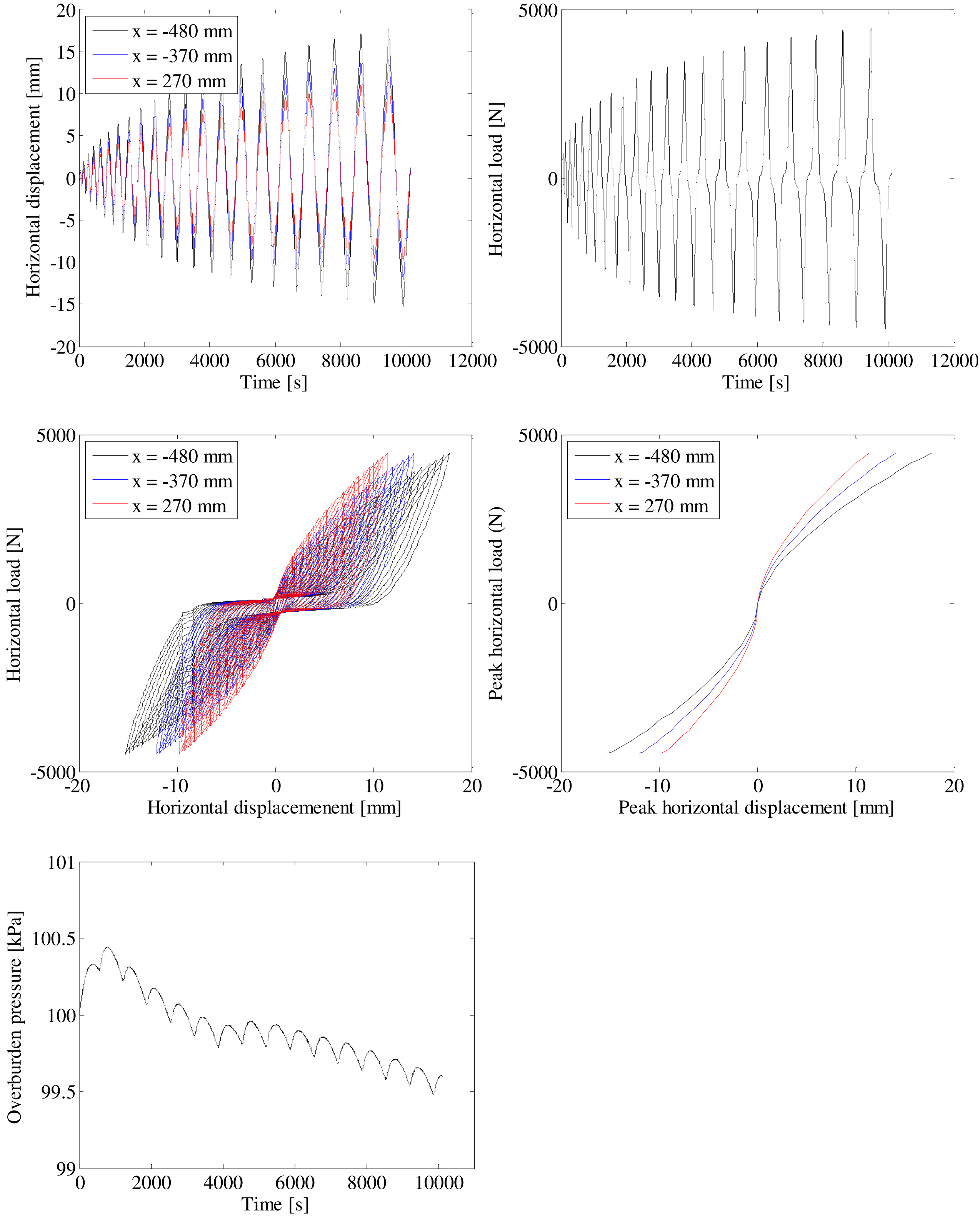

FIGURE 9. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 7: D = 80 mm, L_p = 400 mm and P_0 = 0 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** Summer 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 400	**Overburden pressure (kPa):** 0
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments:	

Soil parameters:

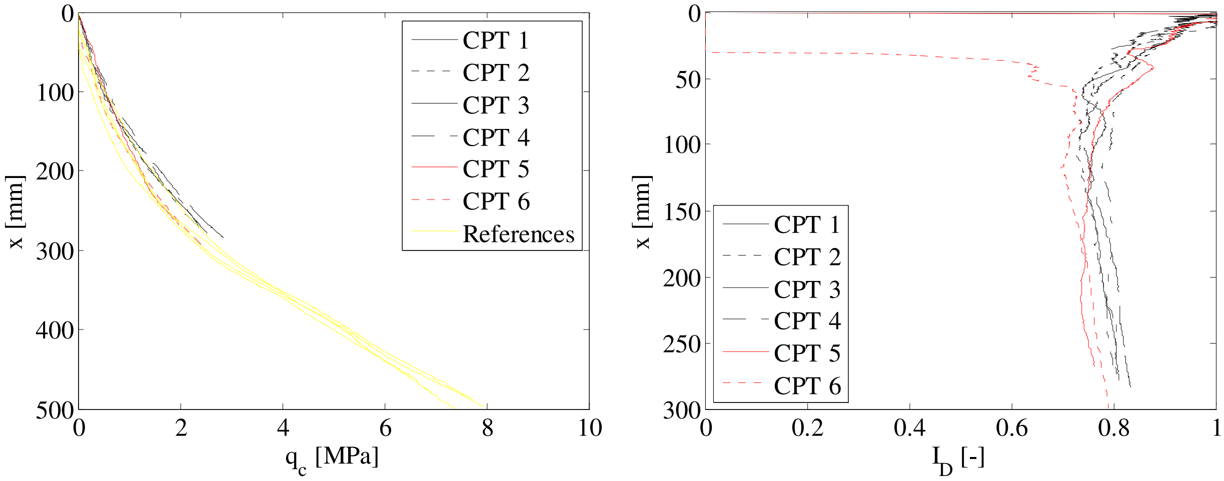

FIGURE 10. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 8. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[∘]	[∘]	[kN/m^3]	[MPa]	[-]
0.77	52.5	17.8	10.2	-	0.23

Test results:

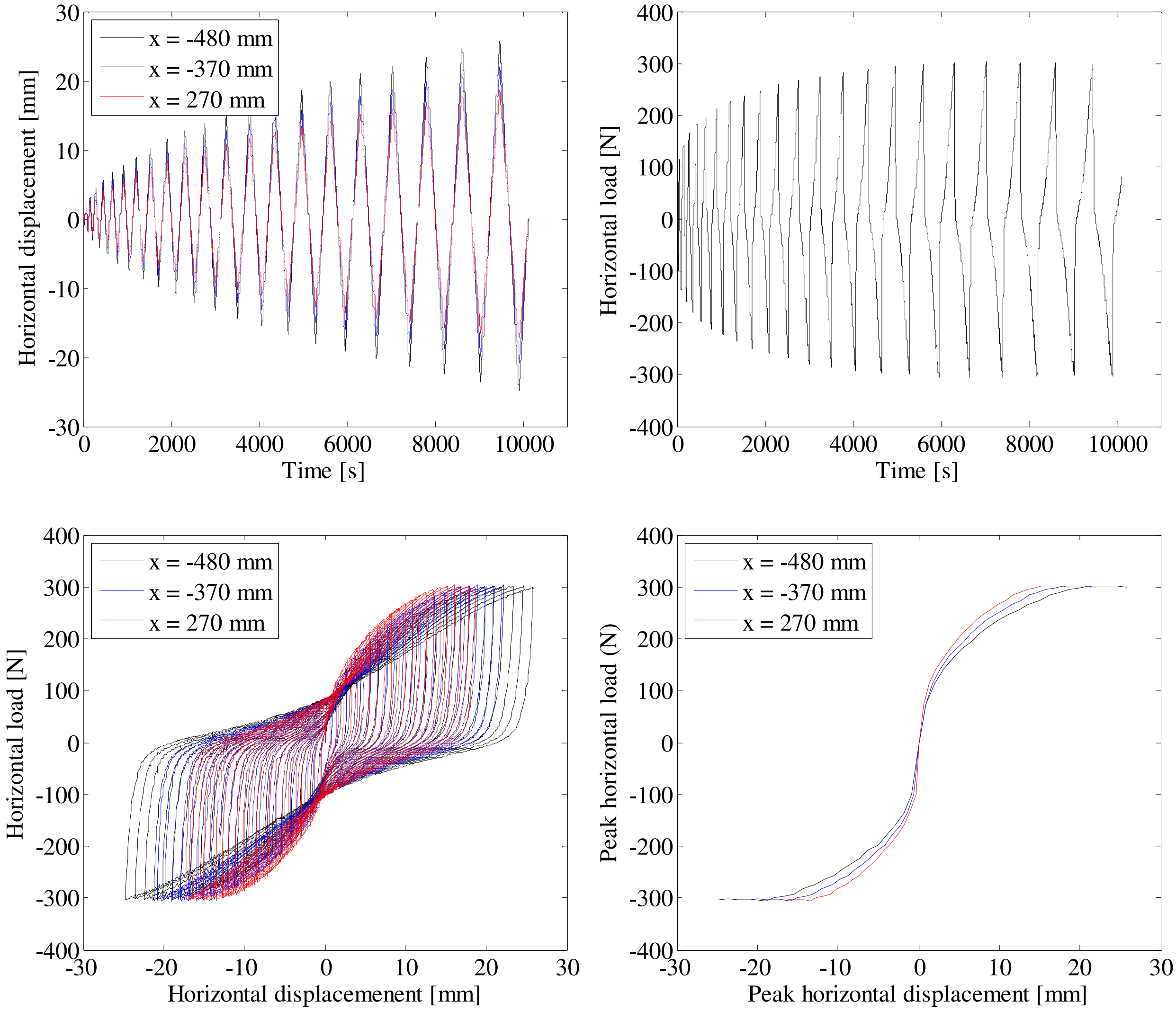

FIGURE 11. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT.

Test 8: D = 80 mm, L_p = 400 mm and P_0 = 25 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 1/9 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 400	**Overburden pressure (kPa):** 25
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 2-3 l/hour.	

Soil parameters:

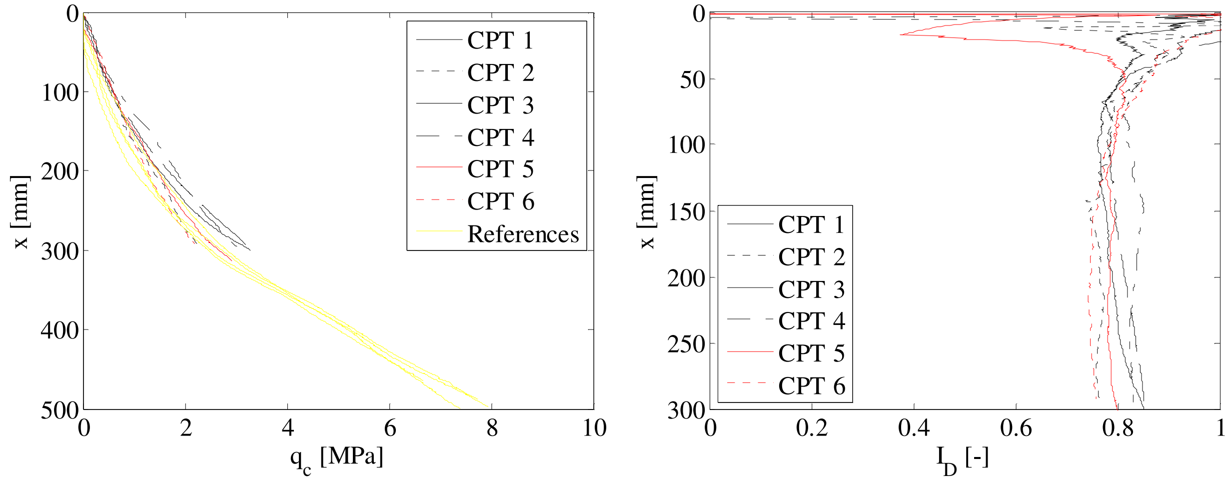

FIGURE 12. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 9. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.79	52.2	18.1	10.2	15.6	0.23

Test results:

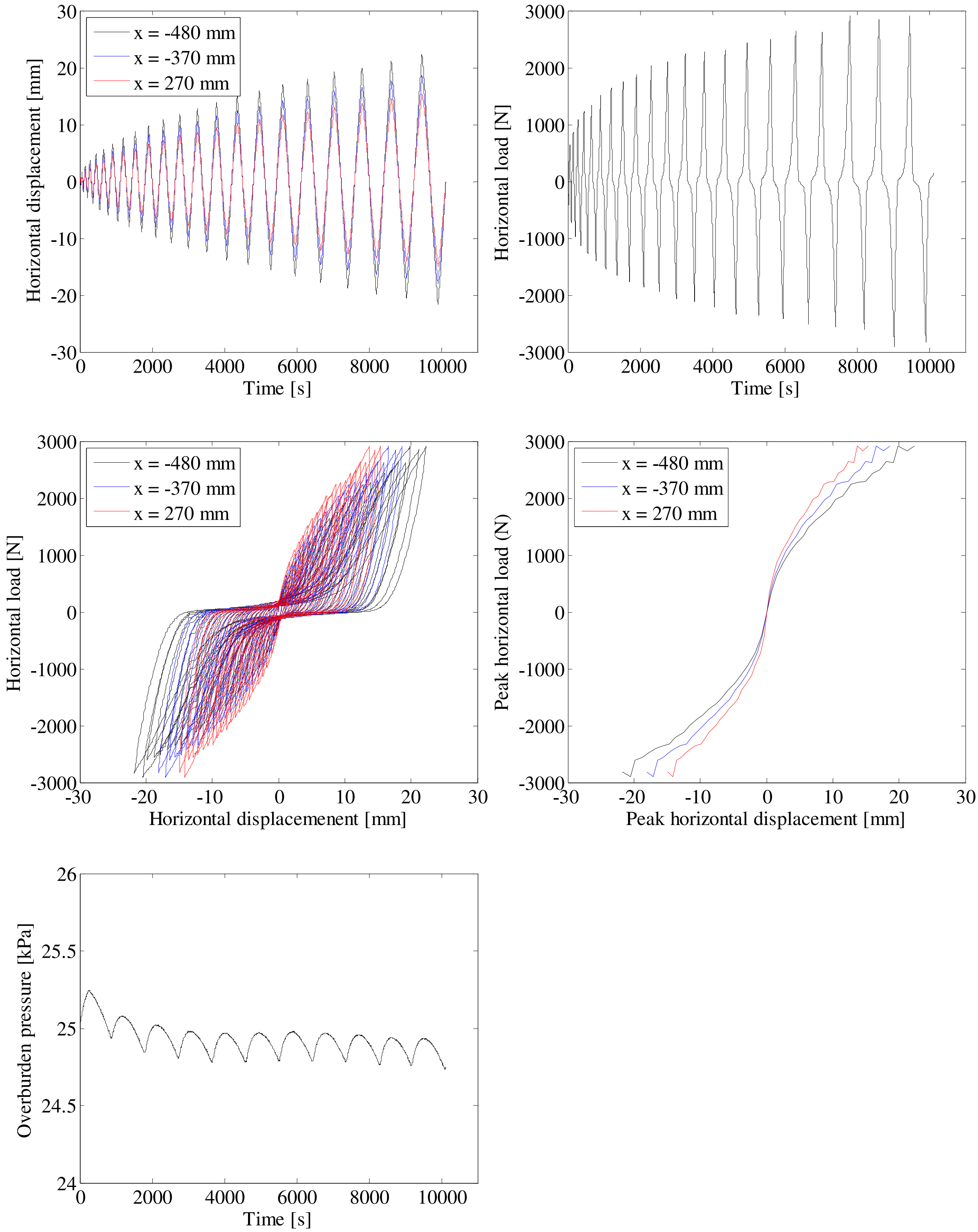

FIGURE 13. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 9: D = 80 mm, L_p = 400 mm and P_0 = 50 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 22/8 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 400	**Overburden pressure (kPa):** 50
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 6 l/hour.	

Soil parameters:

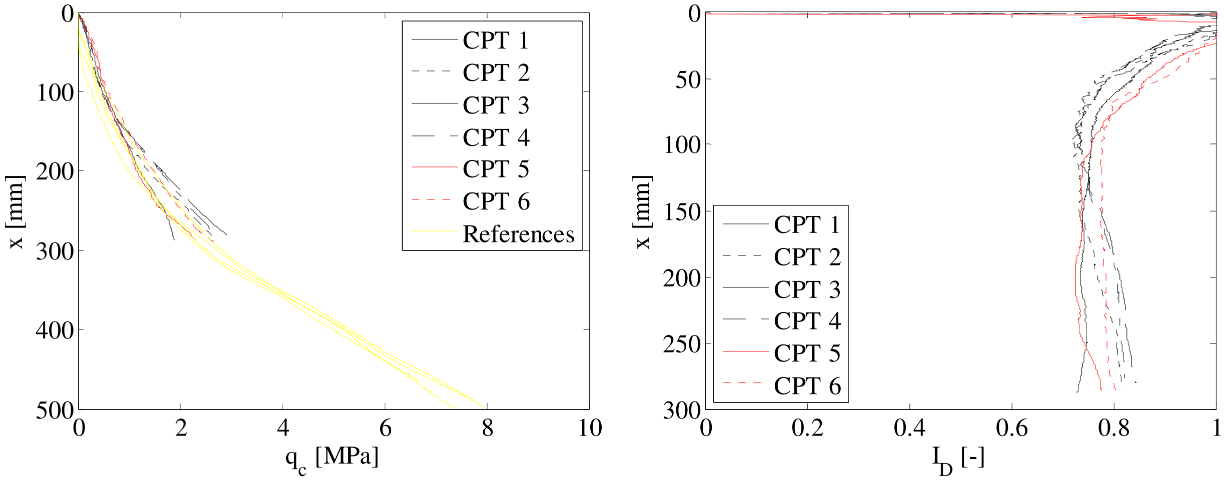

FIGURE 14. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 10. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.77	48.3	16.7	10.2	24.7	0.23

Test results:

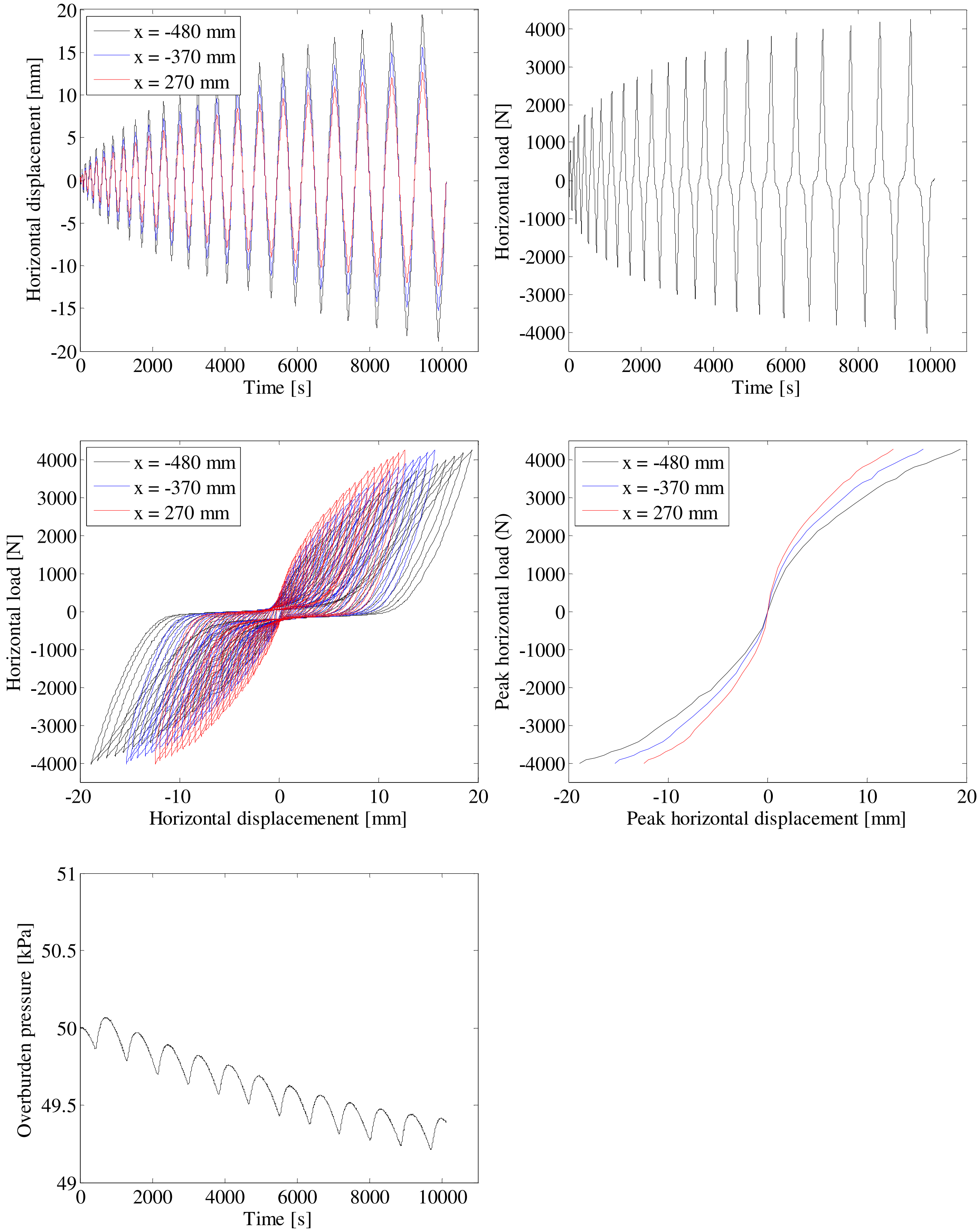

FIGURE 15. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 10: D = 80 mm, L_p = 400 mm and P_0 = 75 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 30/8 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 400	**Overburden pressure (kPa):** 75
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 6-10 l/hour. The screw attaching the force transducer to the hydraulic piston was loose. Therefore the displacement pattern of the pile was not as desired.	

Soil parameters:

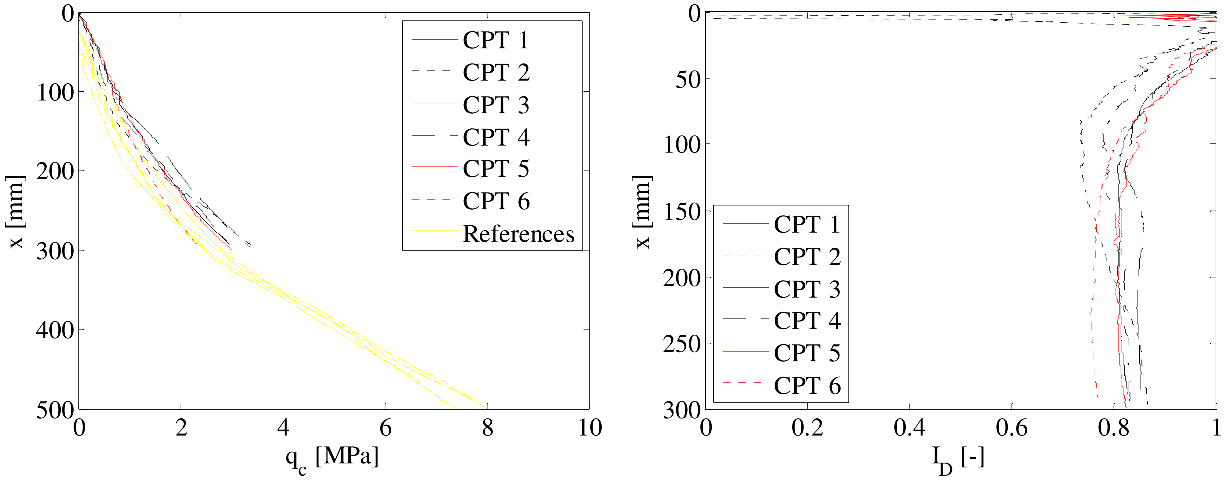

FIGURE 16. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 11. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.81	47.4	17.0	10.2	35.4	0.23

Test results:

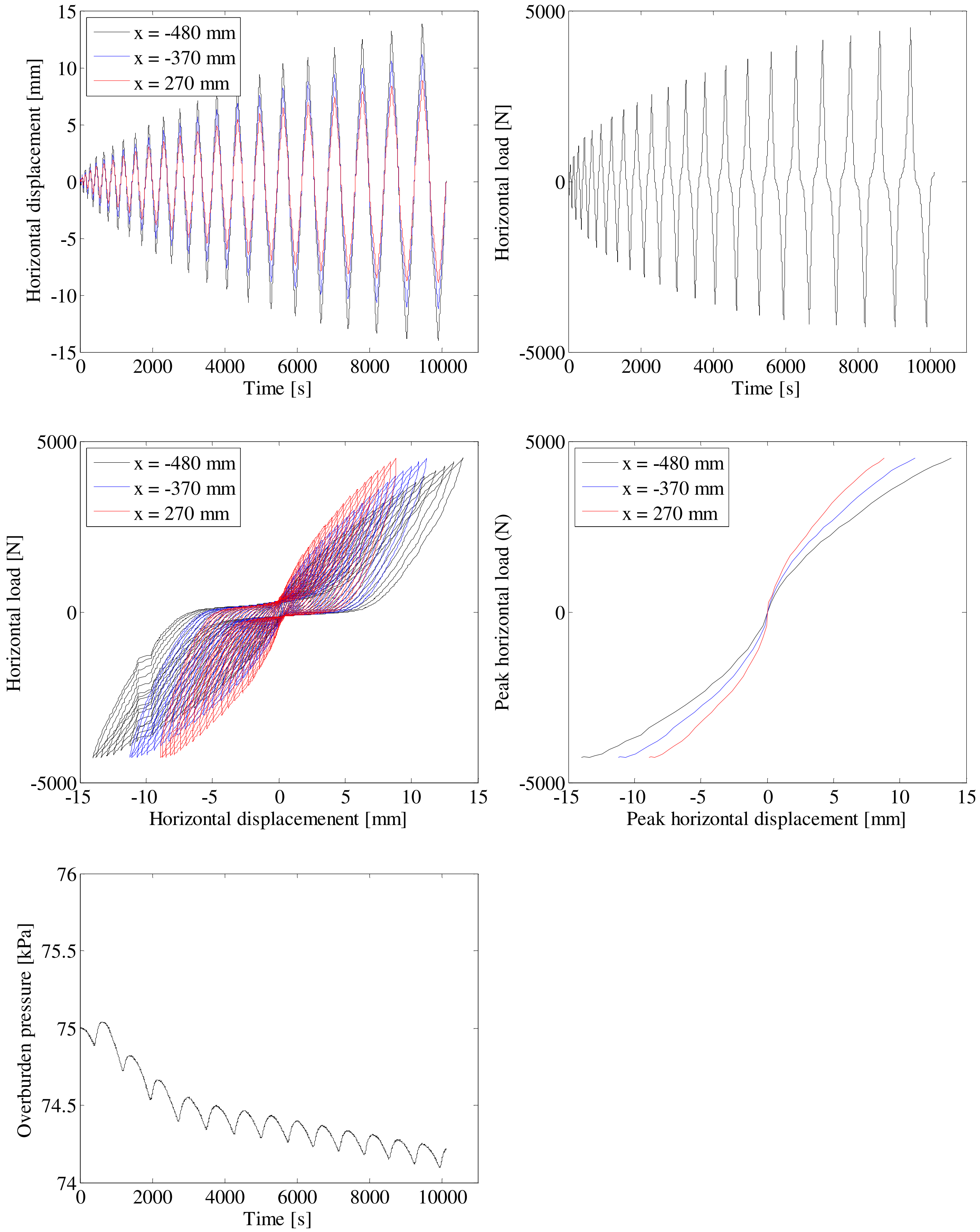

FIGURE 17. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 11: D = 80 mm, L_p = 400 mm and P_0 = 100 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 29/8 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 400	**Overburden pressure (kPa):** 100
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 9 l/hour. The screw attaching the force transducer to the hydraulic piston was loose. Therefore the displacement pattern of the pile was not as desired.	

Soil parameters:

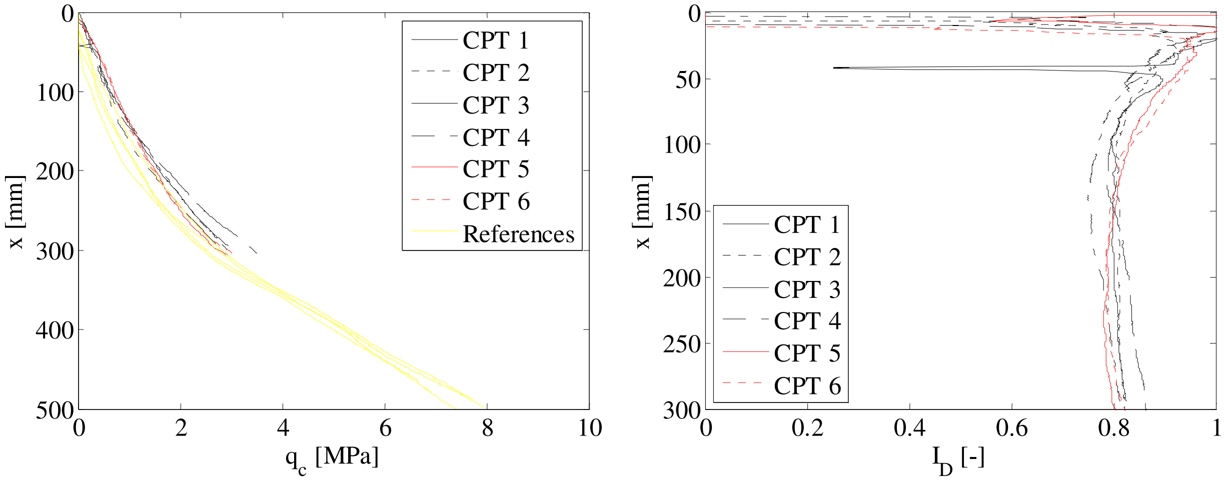

FIGURE 18. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 12. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.80	46.2	16.5	10.2	42.2	0.23

Test results:

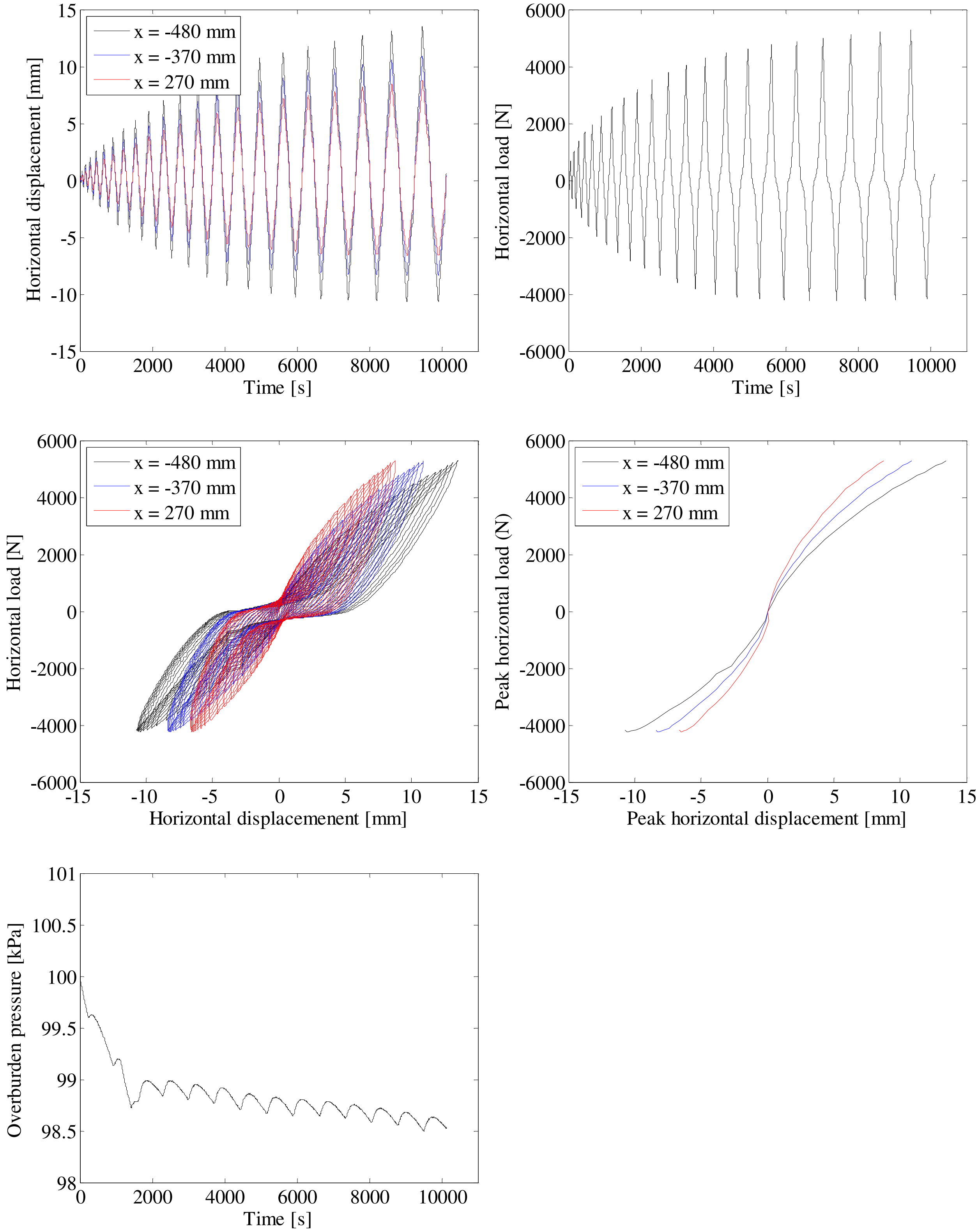

FIGURE 19. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 12: D = 80 mm, L_p = 480 mm and P_0 = 0 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 18/9 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 480	**Overburden pressure (kPa):** 0
Slenderness ratio, *L/D*: 6	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Strain gauge 1 did not work.	

Soil parameters:

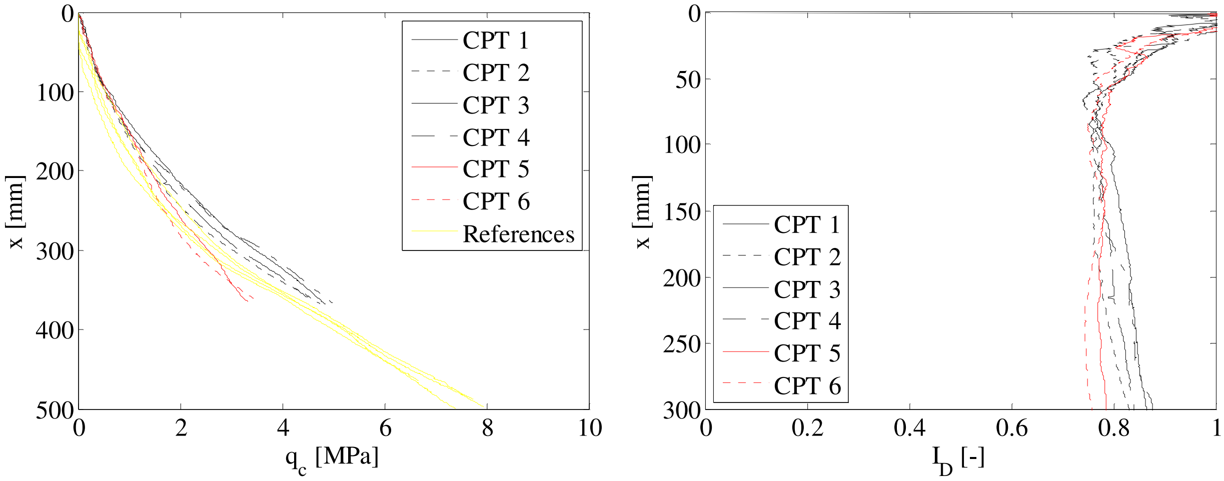

FIGURE 20. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 13. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[∘]	[∘]	[kN/m^3]	[MPa]	[-]
0.81	53.0	18.5	10.2	-	0.23

Test results:

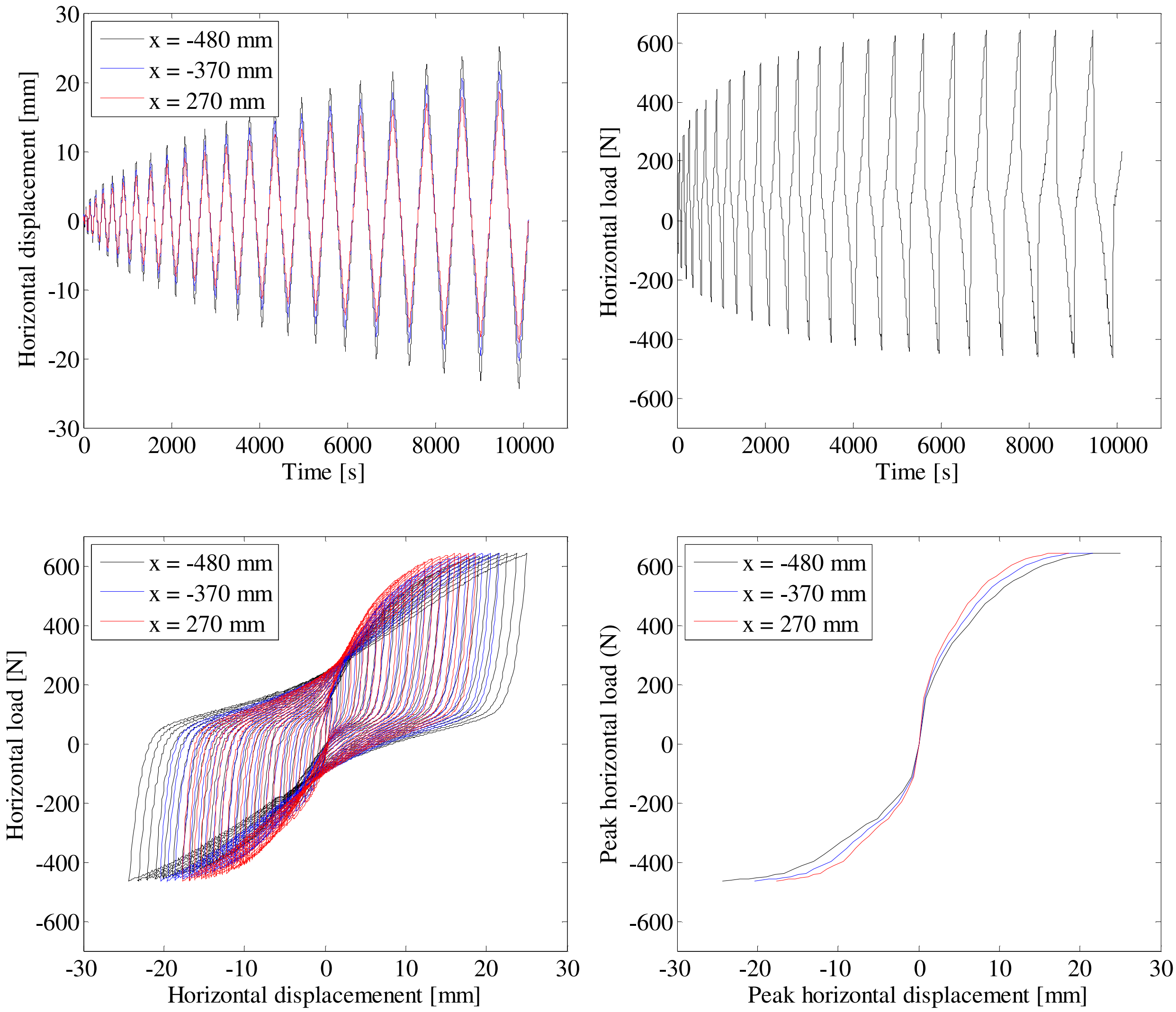

FIGURE 21. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT.

Test 13: D = 80 mm, L_p = 480 mm and P_0 = 50 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 7/9 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 480	**Overburden pressure (kPa):** 50
Slenderness ratio, *L/D*: 6	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 5 l/hour. The screw attaching the force transducer to the hydraulic piston was loose. Therefore the displacement pattern of the pile was not as desired.	

Soil parameters:

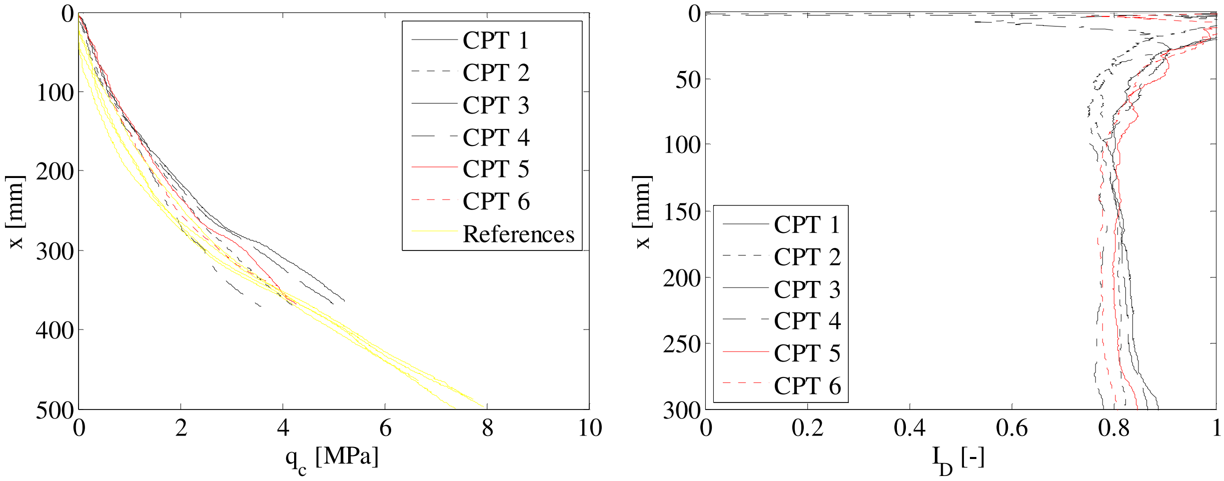

FIGURE 22. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 14. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.82	49.0	17.5	10.2	26.9	0.23

Test results:

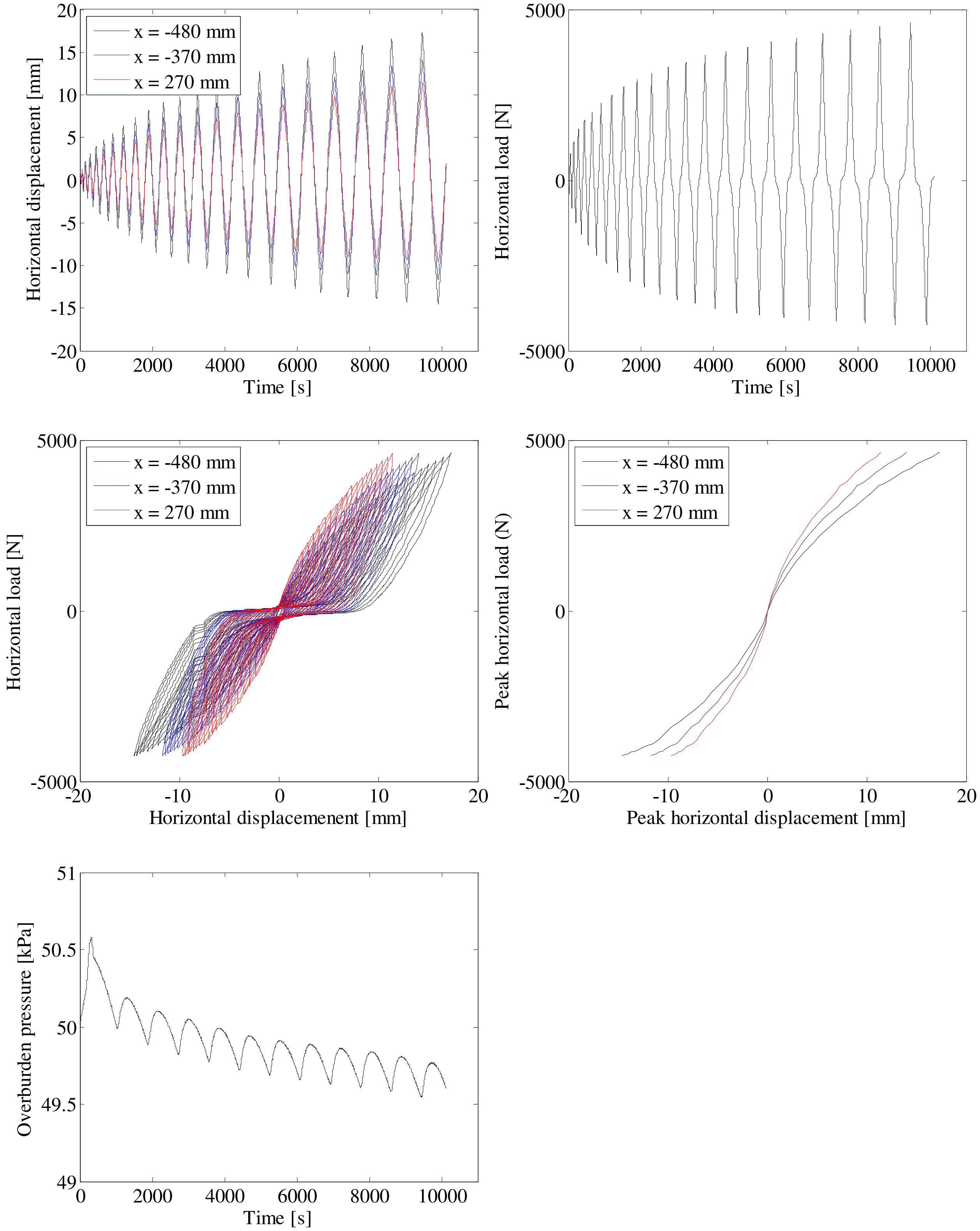

FIGURE 23. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 14: D = 80 mm, L_p = 480 mm and P_0 = 100 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** 11/9 2011
Pile diameter (mm): 80	**No. of strain gauge levels:** 11(All below soil surface)
Embedded pile length (mm): 480	**Overburden pressure (kPa):** 100
Slenderness ratio, *L/D*: 6	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** L. Mikalauskas
Comments: Water flow of approximately 15 l/hour. The screw attaching the force transducer to the hydraulic piston was loose. Therefore the displacement pattern of the pile was not as desired. The pile was moved vertically 1 cm prior to the test.	

Soil parameters:

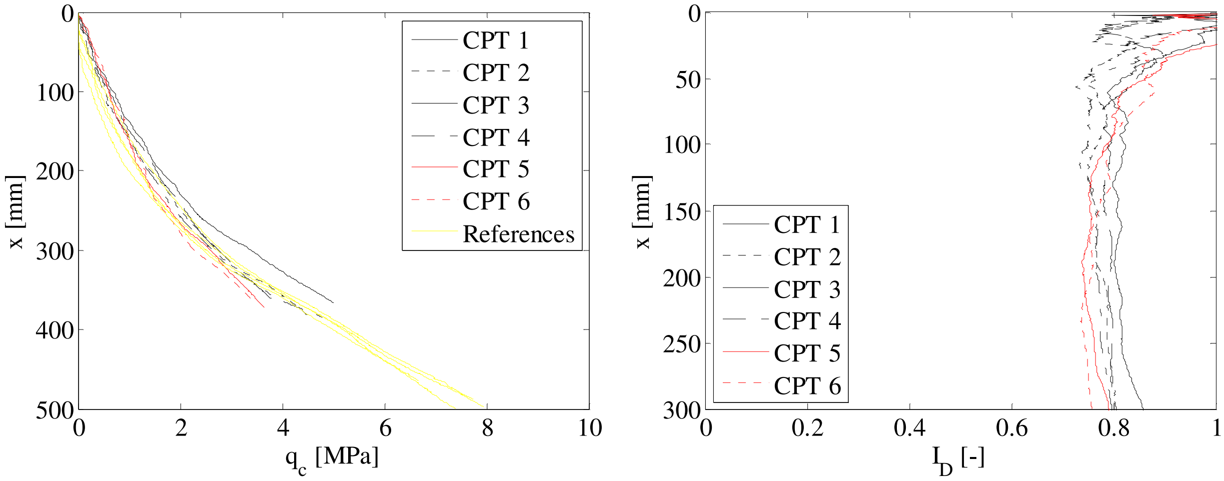

FIGURE 24. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 15. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[∘]	[∘]	[kN/m^3]	[MPa]	[-]
0.79	46.0	16.2	10.2	41.2	0.23

Test results:

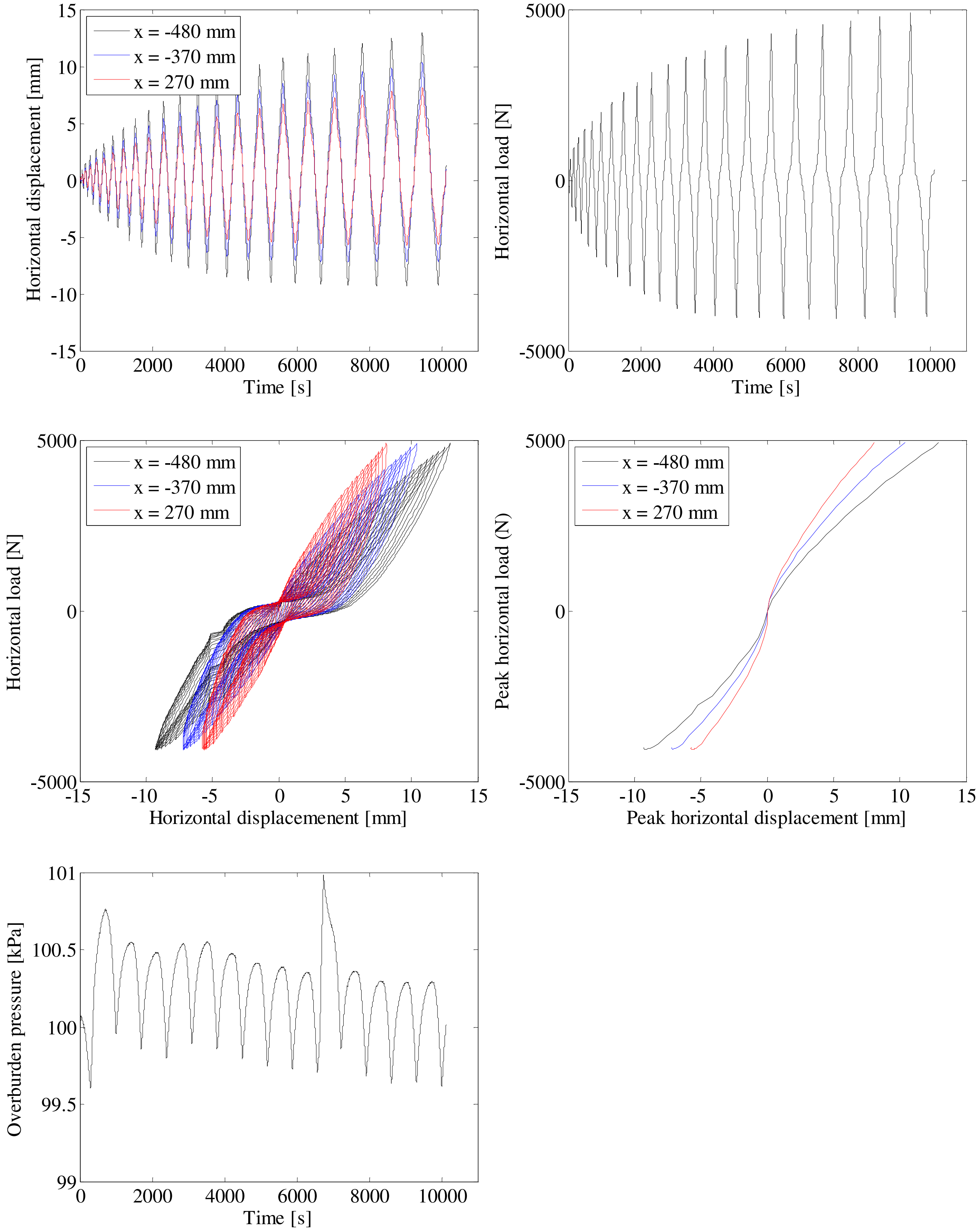

FIGURE 25. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT – BOTTOM LEFT: TANK PRESSURE VERSUS TIME.

Test 15: D = 100 mm, L_p = 500 mm and P_0 = 0 kPa (Closed-ended)

Pile type: Closed-ended	**Completed:** Summer 2011
Pile diameter (mm): 100	**No. of strain gauge levels:** 0 (All below soil surface)
Embedded pile length (mm): 500	**Overburden pressure (kPa):** 0
Slenderness ratio, *L/D*: 5	**Load eccentricity (mm):** 370
Pile wall thickness (mm): 5	**By:** S. P. H. Sørensen and L. Mikalauskas
Comments: A maximum was set for the size of the output file causing the test to stop twice. After each stop the pile displacement started from zero.	

Soil parameters:

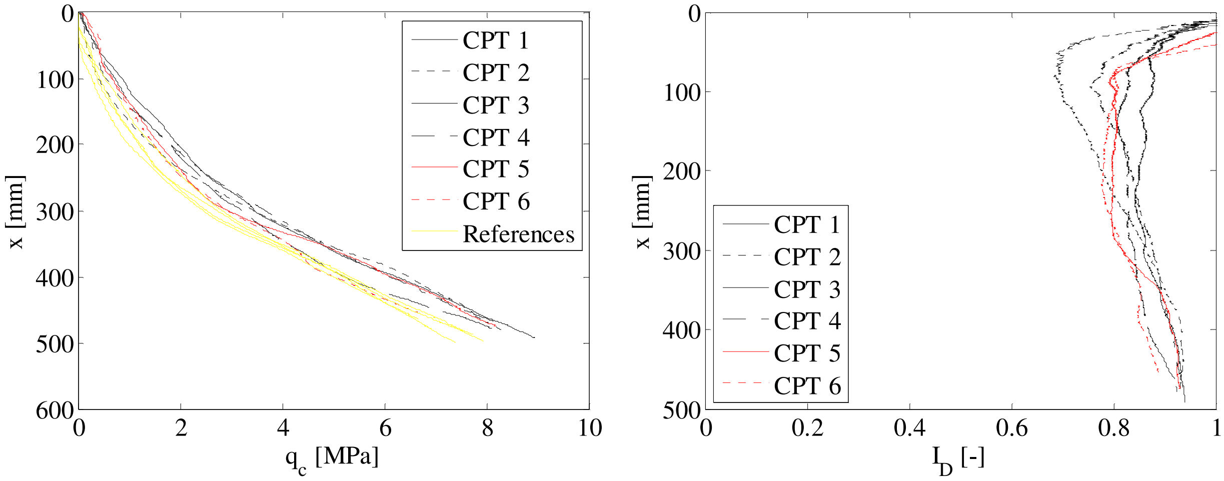

FIGURE 26. CPT-RESULTS. LEFT: TIP RESISTANCE VERSUS DEPTH – RIGHT: RELATIVE DENSITY VERSUS DEPTH.

TABLE 16. ESTIMATED SOIL PARAMETERS.

Relative density, I_D	Internal friction angle, φ_{tr}	Dilatancy angle, ψ_{tr}	Effective unit weight, γ'	Tangential Young's modulus of elasticity, E_0	Poisson's ratio, ν
[-]	[◦]	[◦]	[kN/m^3]	[MPa]	[-]
0.85	53.6	19.4	10.3	-	0.23

Test results:

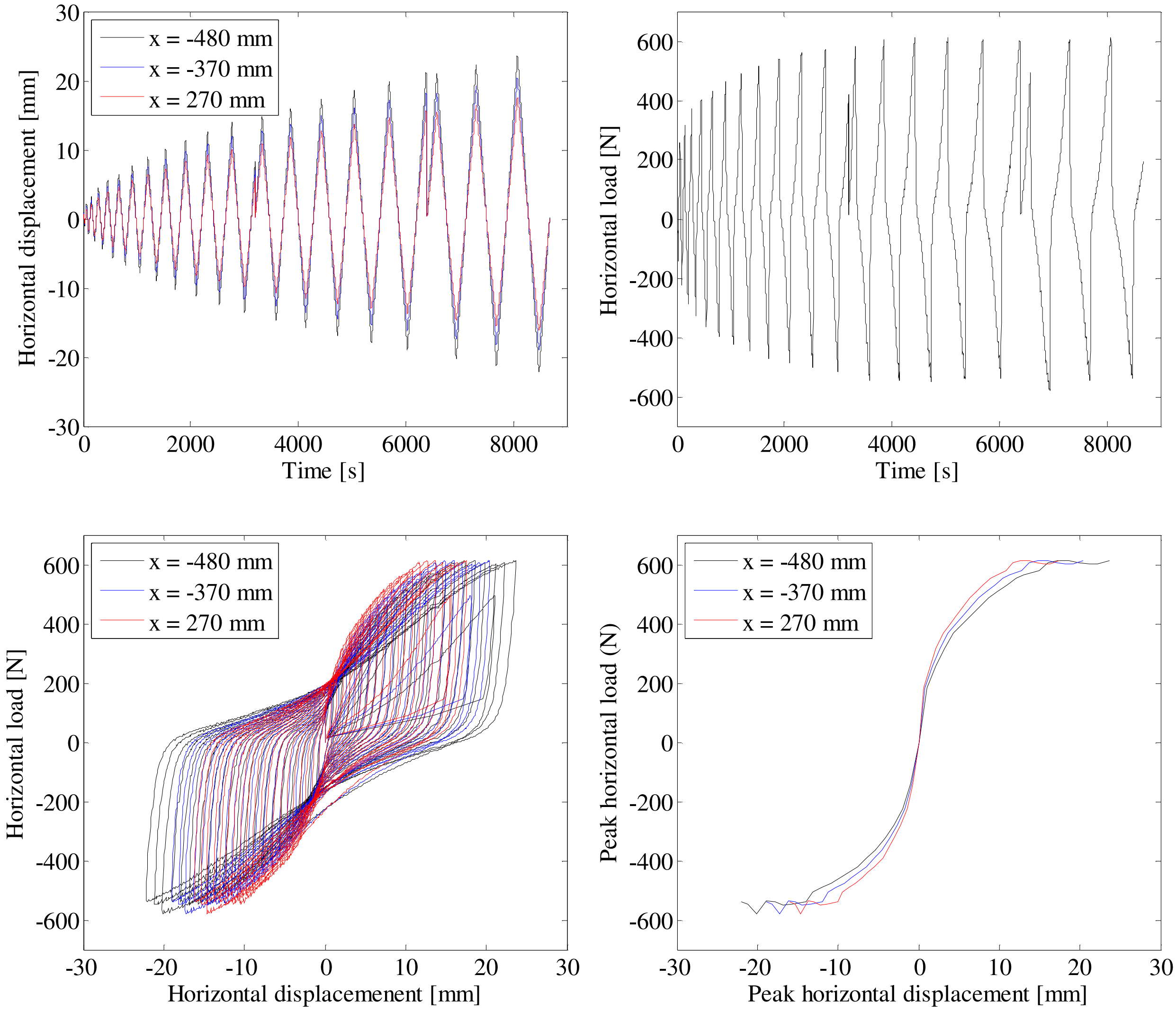

FIGURE 27. TOP LEFT: PILE DISPLACEMENT VERSUS TIME – TOP RIGHT: HORIZONTAL LOAD VERSUS TIME – CENTER LEFT: HORIZONTAL LOAD VERSUS PILE DISPLACEMENT – CENTER RIGHT: PEAK HORIZONTAL LOAD VERSUS PEAK HORIZONTAL DISPLACEMENT.

Comparison with quasi-static tests

In the following the load-displacement relationships from the cyclic small-scale tests are compared with the quasi-static small-scale tests conducted by Sørensen and Ibsen (2011). Both test series have been conducted in a pressure tank at Aalborg University. The only differences between the tests is the applied loading and that a wire was used to attach the pile to the hydraulic piston for the quasi-static tests while a bar was used for the cyclic tests hereby enabling two-way loading.

Load-displacement relationships

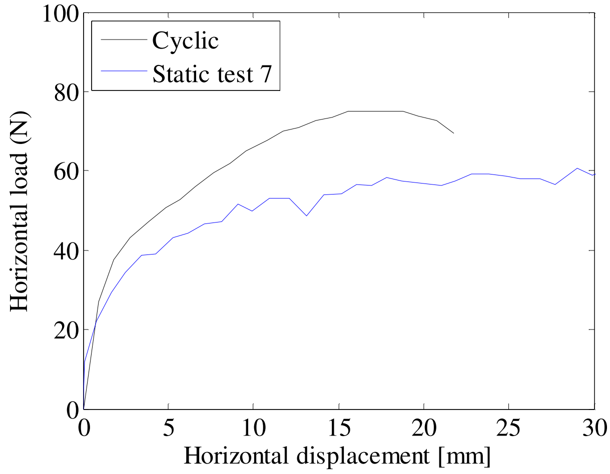

FIGURE 28. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. *D* = 80 mm, L_P = 240 mm, P_0 = 0 kPa.

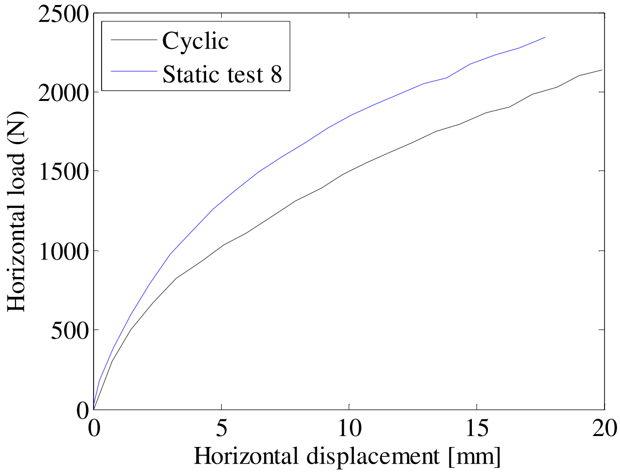

FIGURE 29. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. *D* = 80 mm, L_P = 240 mm, P_0 = 50 kPa.

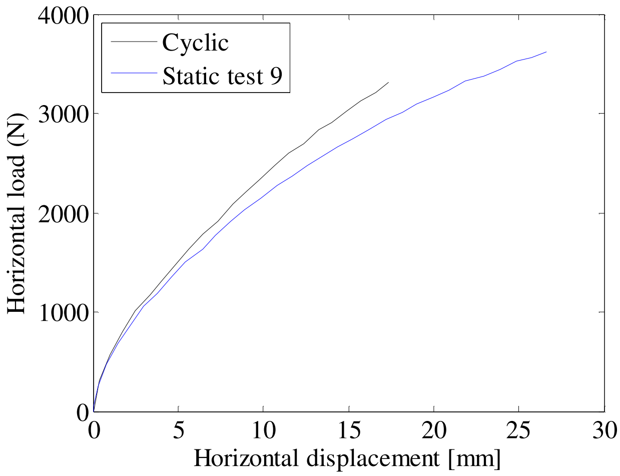

FIGURE 30. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 240 mm, P_0 = 100 kPa.

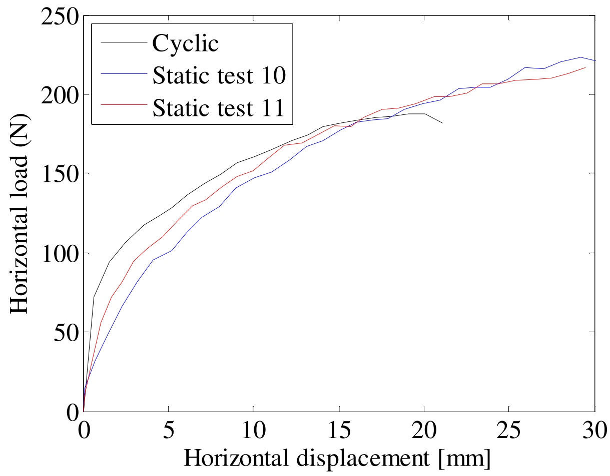

FIGURE 31. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 320 mm, P_0 = 0 kPa.

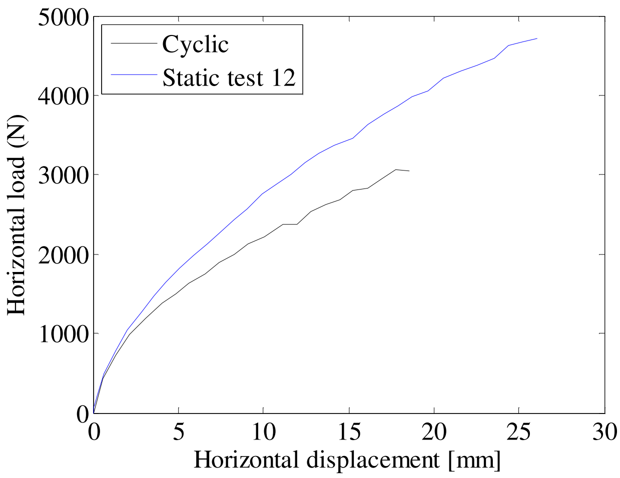

FIGURE 32. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 320 mm, P_0 = 50 kPa.

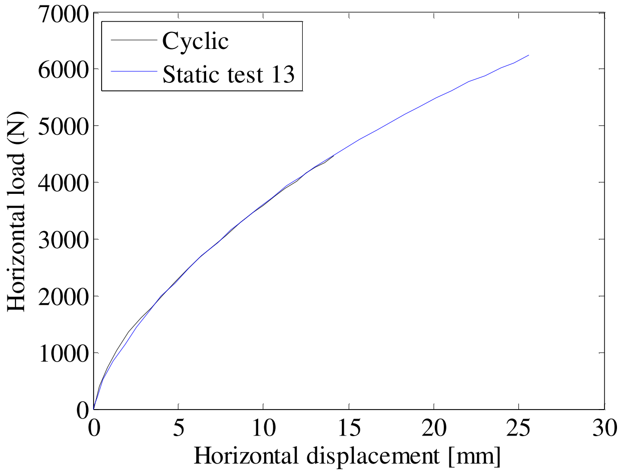

FIGURE 33. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. *D* = 80 mm, L_P = 320 mm, P_0 = 100 kPa.

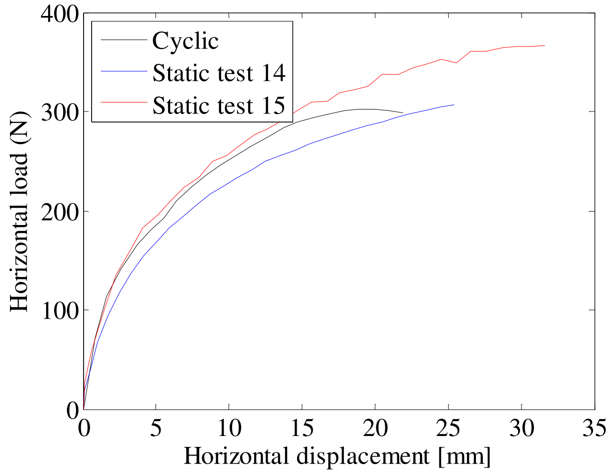

FIGURE 34. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. *D* = 80 mm, L_P = 400 mm, P_0 = 0 kPa.

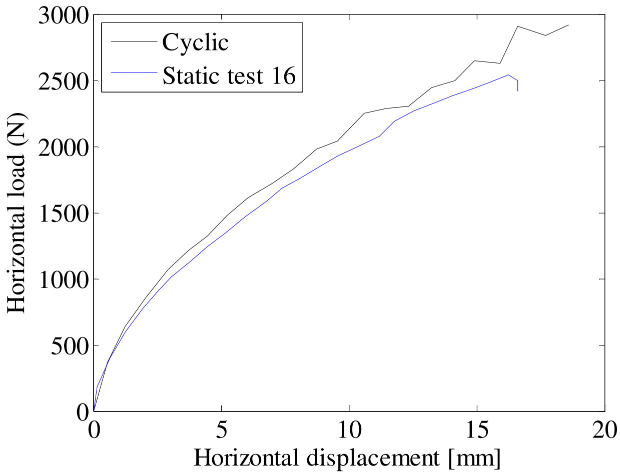

FIGURE 35. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. *D* = 80 mm, L_P = 400 mm, P_0 = 25 kPa.

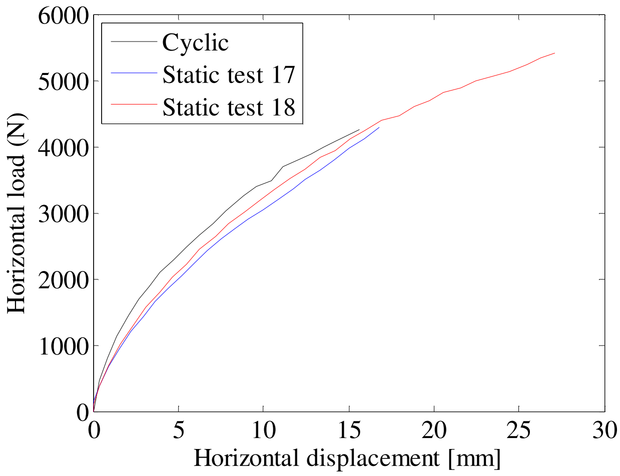

FIGURE 36. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 400 mm, P_0 = 50 kPa.

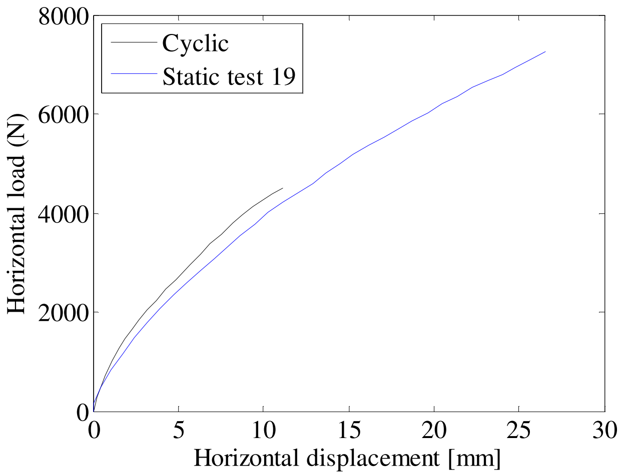

FIGURE 37. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 400 mm, P_0 = 75 kPa.

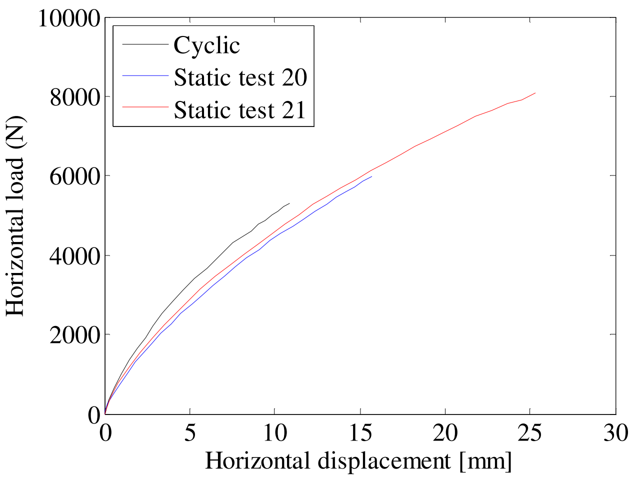

FIGURE 38. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 400 mm, P_0 = 100 kPa.

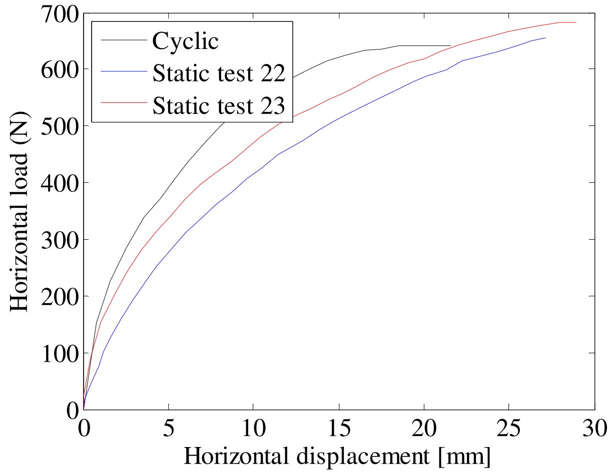

FIGURE 39. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 480 mm, P_0 = 0 kPa.

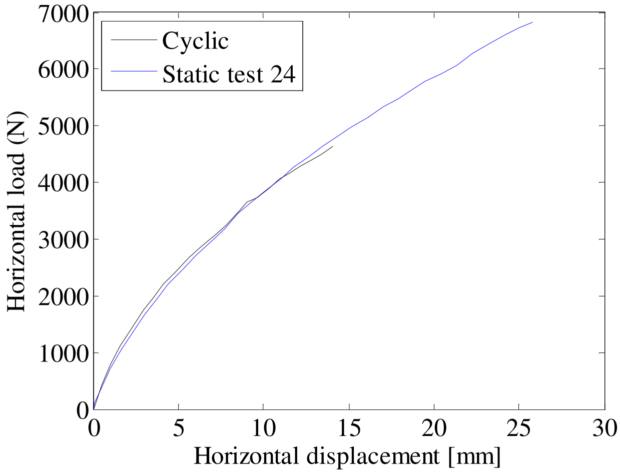

FIGURE 40. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 480 mm, P_0 = 50 kPa.

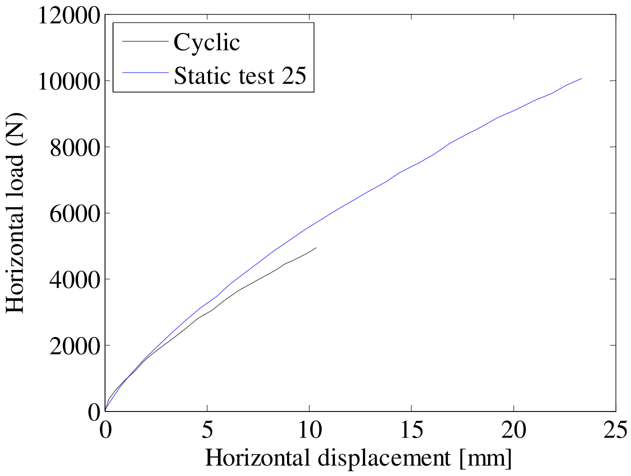

FIGURE 41. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 80 mm, L_P = 480 mm, P_0 = 100 kPa.

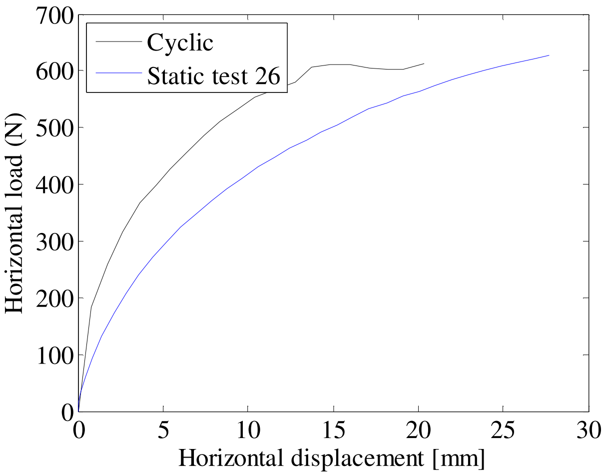

FIGURE 42. COMPARISON OF THE LOAD-DISPLACEMENT RELATIONSHIP FROM THE CYCLIC TESTS WITH THE QUASI-STATIC TESTS. D = 100 mm, L_P = 500 mm, P_0 = 0 kPa.

Acknowledgements

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